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A Search for Metal Lines in the Spectra of
DA White Dwarfs

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ABSTRACT

During the interval of time, October 1, 1984 to March 31, 1985, a considerable amount of the research effort connected with Grant NAG5-287 from the National Aeronautics and Space Administration has been to carry out theoretical analyses in order to interpret the ultraviolet spectra of DB white dwarfs obtained earlier with the *International Ultraviolet Explorer (IUE)* satellite. Here the results of the *IUE* ultraviolet spectroscopy combined with visual data and model atmospheres of DB white dwarfs are reported. The model atmospheres were obtained in collaboration with E. P. Nelan. In particular, a search for spectral lines due to the element carbon using the ultraviolet was made. In no case, is there a positive detection of carbon and from these data, and upper limits for carbon by number relative to helium are derived in the range of $C: He < 10^{-5}$ to 10^{-7} for the 16 DB stars with ultraviolet spectra in the temperature range $11400\text{ K} < T_{\text{eff}} < 23000\text{ K}$. The low carbon abundances found in the atmospheres of the DB stars agrees well with the hypothesis that the atmospheric carbon observed in the cooler DQ members of the helium-rich white dwarf sequence is produced by a convective dredging mechanism.

I. INTRODUCTION

The helium-rich DB stars are the spectroscopic subgroup of the white dwarfs characterized by spectra dominated by He I lines. Recent studies of the DB, (e.g. Koester, Schulz, and Wegner 1981; Wickramasinghe 1983; Wickramasinghe and Reid 1983; Oke, Weidemann, and Koester 1984) have provided a more reliable effective temperature scale and indicated that the mean DB mass is close to the $0.6 M_{\odot}$ found for the DA stars (Cf. Koester, Schulz, and Weidemann 1979). Nevertheless, fundamental questions about the atmospheres, origin, and evolution of the DB stars still remain. Some authors have argued that the DB can evolve from the DA when they cool and convection mixes the thin superficial hydrogen layer into the helium-rich envelope. Also, it has been suggested that a DB can change into a DA if it accretes hydrogen from interstellar clouds. Other investigators have proposed that the hydrogen and helium-rich white dwarfs arise due to differences in their progenitor stars. M_{\odot} (Winget et al. 1981; Winget and Fontaine 1982).

Additional information on the white dwarf envelope structures comes from the appearance of carbon in the atmospheres of the helium-rich DQ sequence members which lie just below the DB in effective temperature. It appears that accretion is not important for these objects and that the carbon diffuses outwards from the core due to an abundance gradient and then is brought to the surface by convection. According to preliminary calculations by

Fontaine et al. (1984) and more detailed time dependant diffusion calculations by Pelletier et al. (1985), the surface carbon abundance depends on the mass of the outer helium layer and therefore is a probe of the star's envelope. The shape of the curve of carbon abundance as a function of effective temperature also depends on the details of the convection theory and this picture explains the existence of the carbon in a restricted range of T_{eff} as observed for the DQ and DC white dwarfs (Wegner 1983a; Wegner and Yackovich 1983,1984). However, up until the present, no meaningful empirical carbon abundances had been carried out for the DB white dwarfs, which represents an extension of the observations of carbon in the atmospheres of the helium-rich sequence to higher effective temperatures than observed in the DQ stars, which is $T_{\text{eff}} \geq 12000$ K.

Consequently, the purpose of this project was to use primarily *IUE* ultraviolet spectroscopic observations of the DB white dwarfs to extend the search for carbon in the atmospheres of members of the helium rich white dwarf sequence to higher effective temperatures in order to test the convective dredging hypothesis which predicts a decreased carbon abundance in the DB relative to their cooler DQ cousins. Here details of the *IUE* observations and resulting upper limits to the carbon abundances derived employing model atmospheres are reported

Table 1
Summary of New IUE Observations of DB Stars

Object/ Coordinates	Image No.	Exposure Time Minutes	Date
LTT11/ 0001-17	SWP 19005 LWR 15057	240 135	83 15
GD408/ 0002+72	SWP 19006 LWR 15058	160 100	83 16
Ton 10/ 0841+26	LWR 15592 SWP 19559	80 135	83 86
GD303/ 1011+57	SWP 18994 LWR 15047	240 150	83 13
PG1411+215/ 1411+21	SWP 18995 LWR 15049	100 65	83 14
PG1445+151 1445+15	SWP 19548 LWR 15584	180 120	83 87
G256-18/ 1459+82	LWR 15577 SWP 19540	120 180	83 84
GD378/ 1822+41	LWR 15578 SWP 19549	65 76	83 84 83 85

Table 2

IUE Observations of DB Stars taken from the Archives

Object/ Coordinates	Image No.	Exposure Time Minutes	Date ID	Program
BPM 17088/ 0308-56	LWR 6462 SWP 7459	22	79 356 65	GV111
BPM17731/ 0418-53	SWP10818 LWR 9504	60 60	80 351	UK321
BPM18164/ 0615-59	SWP 10819 LWR 9505 SWP 14156 LWR 10760	50 50 100 85	80 351 81 153	UK321 UK405
GD385/ 1645+32	SWP 14015 LWR 10668	34 34	81 141	GV555 GV555
L1573-31 1940+37	SWP 14678 LWR 11261	210 135	81 219	FBDJL
BPM26944/ 2034-53	SWP 10813	40	80 349	UK321
LDS749B 2129+00	SWP 14656 LWR 11248 SWP 14127 LWR 10753	210 130 323 62	81 217 81 151	FBDJL FBDJL UK405 UK405
LDS785A/ 2224-344	SWP 10820 LWR 9506	70 52	80 351	UK321 UK321

II. OBSERVATIONS

The ultraviolet observations utilized the low resolution (approximately 7 Å) mode of the *IUE*. Both new observations were secured and older ones were taken from the archives of the National Space Science Data Center. Table 1 summarizes the newer data observed by GW and Table 2 lists the archived spectra used in this investigation. One observational difficulty encountered was that few bright examples of the DB exist and therefore long exposures were normally required which yielded noisy spectra.

Figure 1 shows examples of the SWP spectra listed in Table 1. For reference, the spectrum of the $T_{\text{eff}} = 10600$ K DBQA5 white dwarf LDS678B (Wegner 1981) is displayed at the bottom of the diagram. The SWP portion of that star's spectrum is dominated by C I lines, but comparison with the hotter DB spectra clearly shows that none of these objects display any carbon features in their spectra within the noise level of the data.

Visual spectral scans of 21 objects were obtained using the Image Intensified Dissector Scanner (IIDS) attached to the Kitt Peak 2.1 m telescope during May 1982 and January 1984. These data cover the wavelength interval $\lambda\lambda 3300 - 6900$ with a resolution near 17 Å. Some additional spectra were obtained at the McGraw-Hill Observatory with the Mark II spectrograph attached to the 1.3 m telescope which covers the wavelength interval $\lambda\lambda 4000 - 6900$ at 8 Å resolution. For stars lacking visual spectroscopy, but with

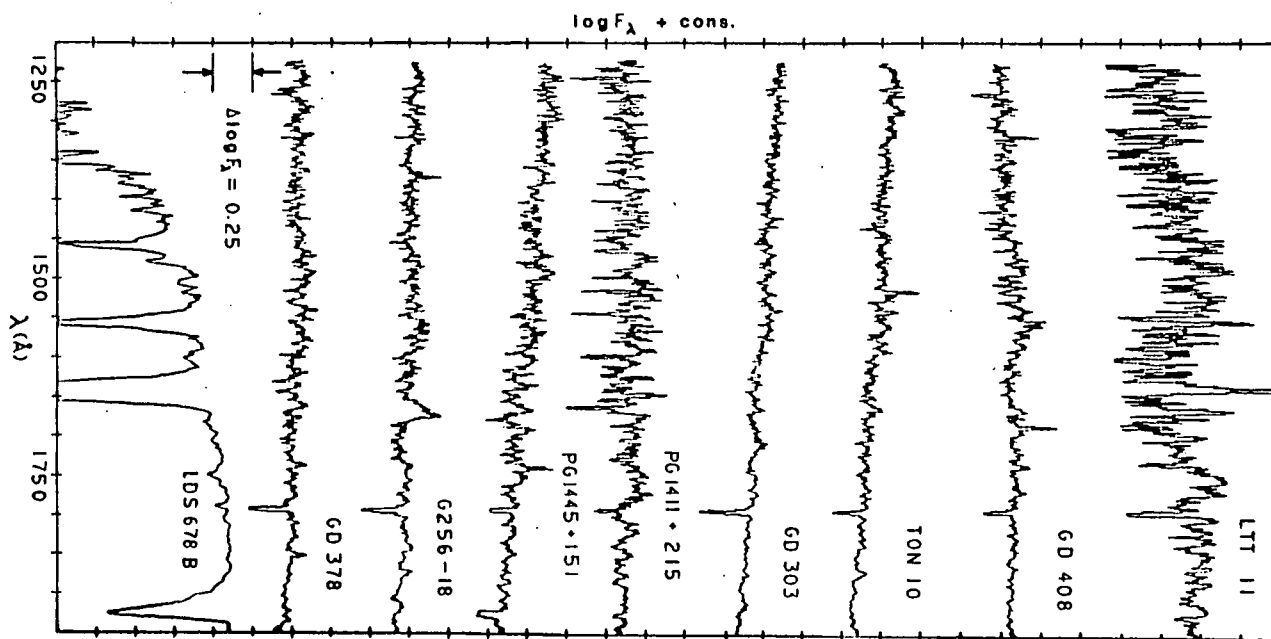


FIG.1. - The *IUE* short wavelength camera (SWP) spectra of the DB stars in Table 1 with original resolution near 7 Å. The spectrum of the well known white dwarf LDS678B (Wegner 1981a) which shows strong C I lines is displayed at the bottom of the figure for comparison. Note that no carbon lines appear in any of the eight upper DB spectra. The sharp depressions near $\lambda\lambda 1800$ and 1925 are instrumental artifacts.

IUE observations, particularly in the South, Stromgren photometry was used from Wegner(1979 and 1983b) and converted to flux.

Figures 2 and 3 display most of the visual spectra of the DB stars. In general, they show no lines of elements other than He I, although certain well known stars such as G210-36 and GD40 have been described elsewhere that do show weak H I and Ca II features. There is no evidence for any of the visual lines of C I or C II in these spectra.

FIG.2. - The visual spectra of some of the DB white dwarfs that have been observed using the Kitt Peak 2.1 m telescope and IIDS detector system. Four of the stars are in common with those in Figure 1. The original resolution was approximately 17 Å.

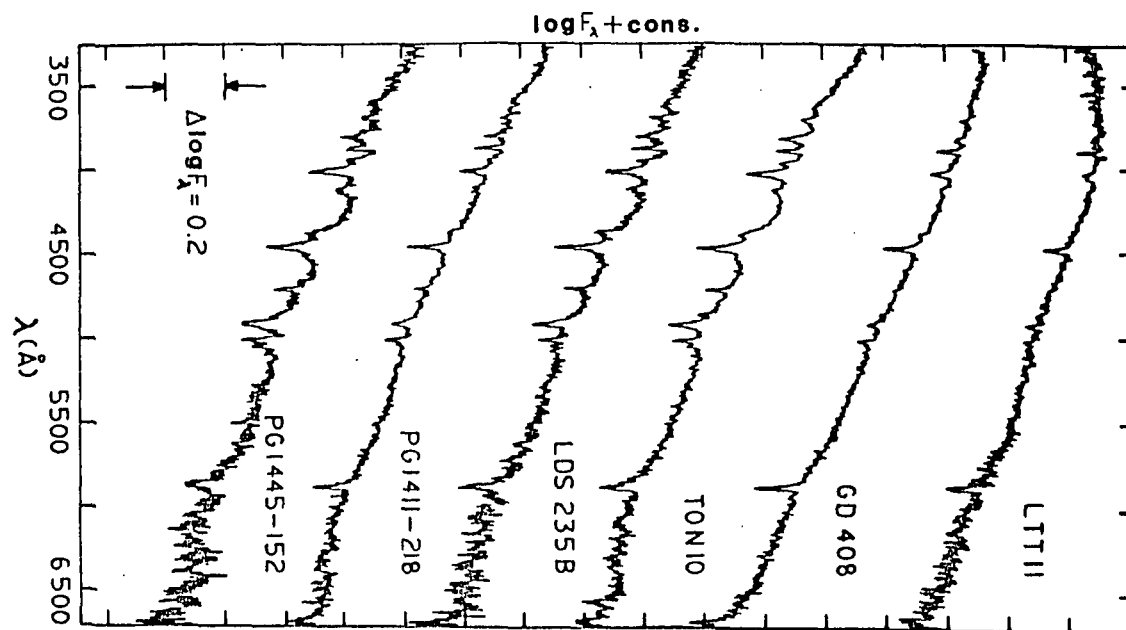
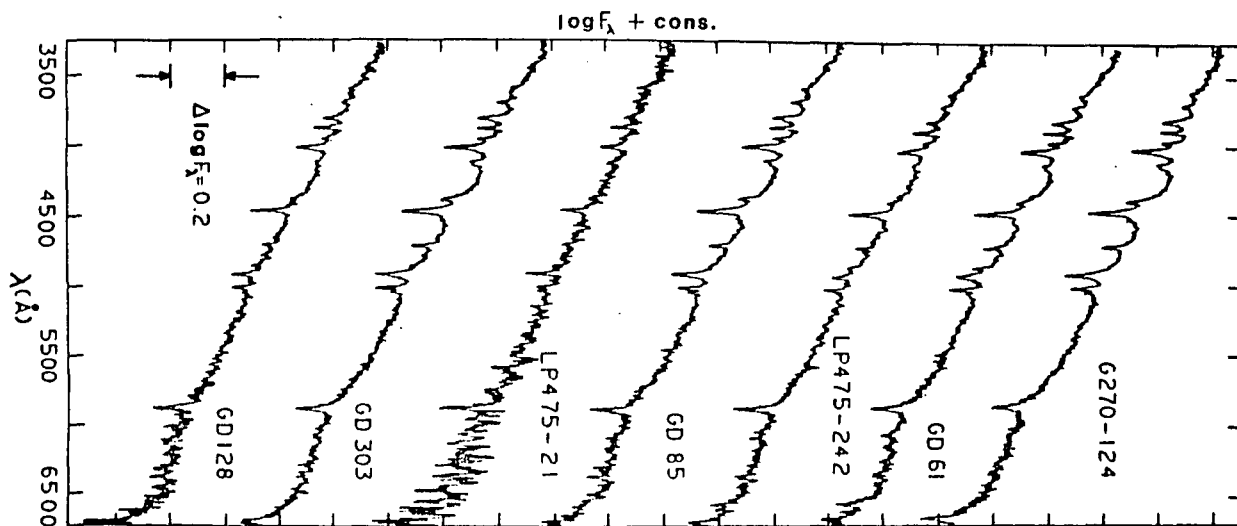


FIG.3. - The visual spectra of additional DB white dwarfs observed with the 2.1 m Kitt Peak telescope and IIDS at an original resolution of approximately 17 Å.



III. DETERMINATION OF UPPER LIMITS TO ATMOSPHERIC CARBON ABUNDANCES IN THE DB WHITE DWARFS

a) Model Atmospheres.

The DB spectra described in the last section have been analyzed in collaboration with Dr. E. P. Nelan who was formerly a graduate student at Dartmouth and who is currently at the Space Telescope Science Institute. He-rich model atmospheres were used and these were calculated at the Kiewit Computation Center at Dartmouth and the Space Telescope Science Institute with the model atmosphere program LUCIFER using VAX 785 computers. Additional details can be found in Nelan (1985). The program generates flux-constant line-blanketed plane parallel model atmospheres employing a complete linearization technique (Mihalas 1978) that has been modified to handle convection as outlined by Grenfell (1972).

A grid of pure He $\log g = 8$ models was constructed to analyze the DB stars. Comparison with a number of models computed with HCNO abundances down to 10^{-4} relative to helium, the upper limit to the abundances considered here, showed that all models with abundances this low were close enough in their structure to justify this simplification. He I, He II, He⁻, and He-He Rayleigh scattering, as computed in the ATLAS program of Kurucz (1970) plus the addition of He I line blanketing as described below were employed as the

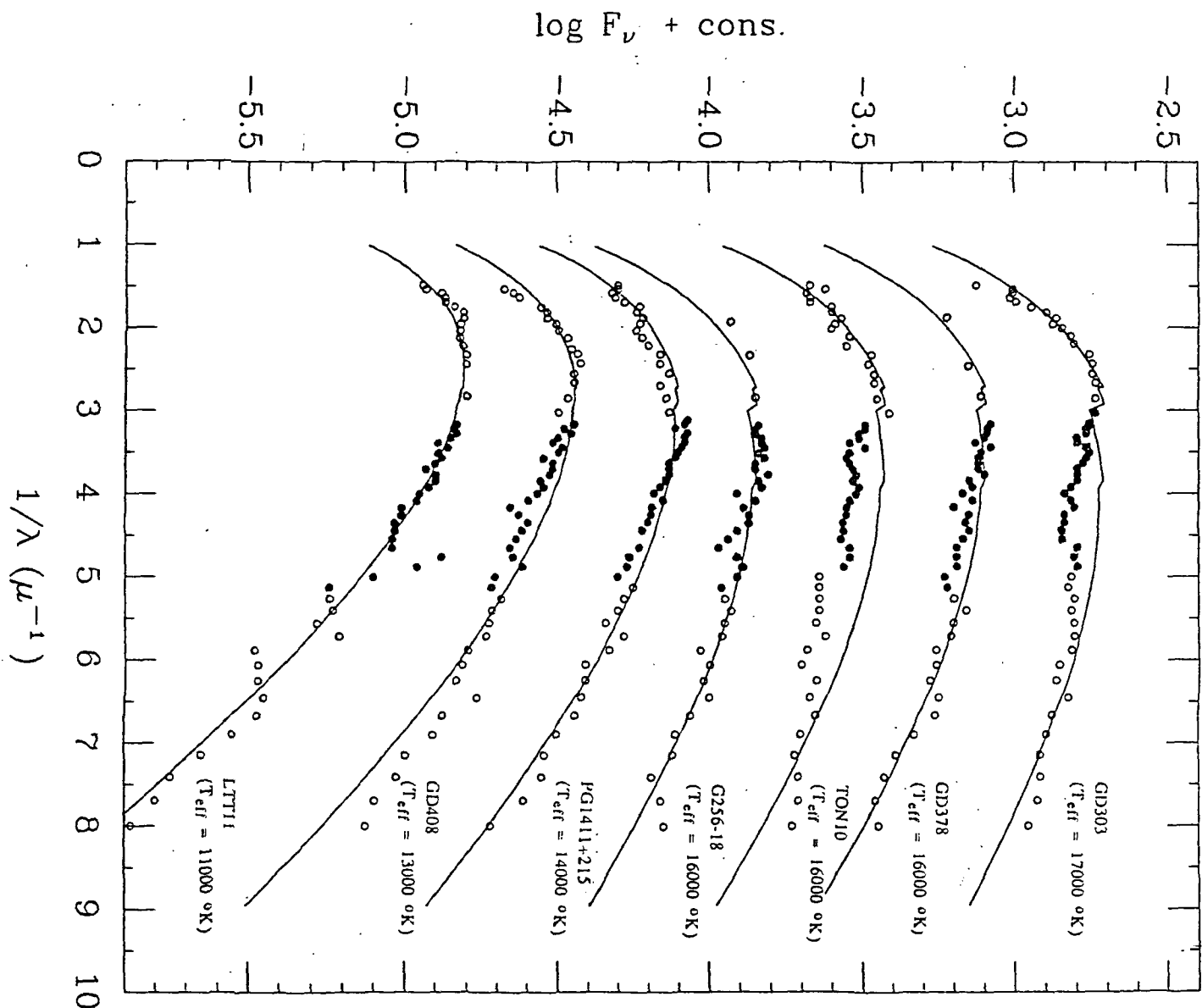


FIG. 4. - Observed continuum data for the DB stars in Table 1 compared with emergent fluxes from the model atmospheres described in the text. Open circles for $1/\lambda > 5$ denote IUE SWP data, while for $1/\lambda < 3$, they indicate visual data. Filled circles show IUE LWR data. For all models, $\log g = 8$.

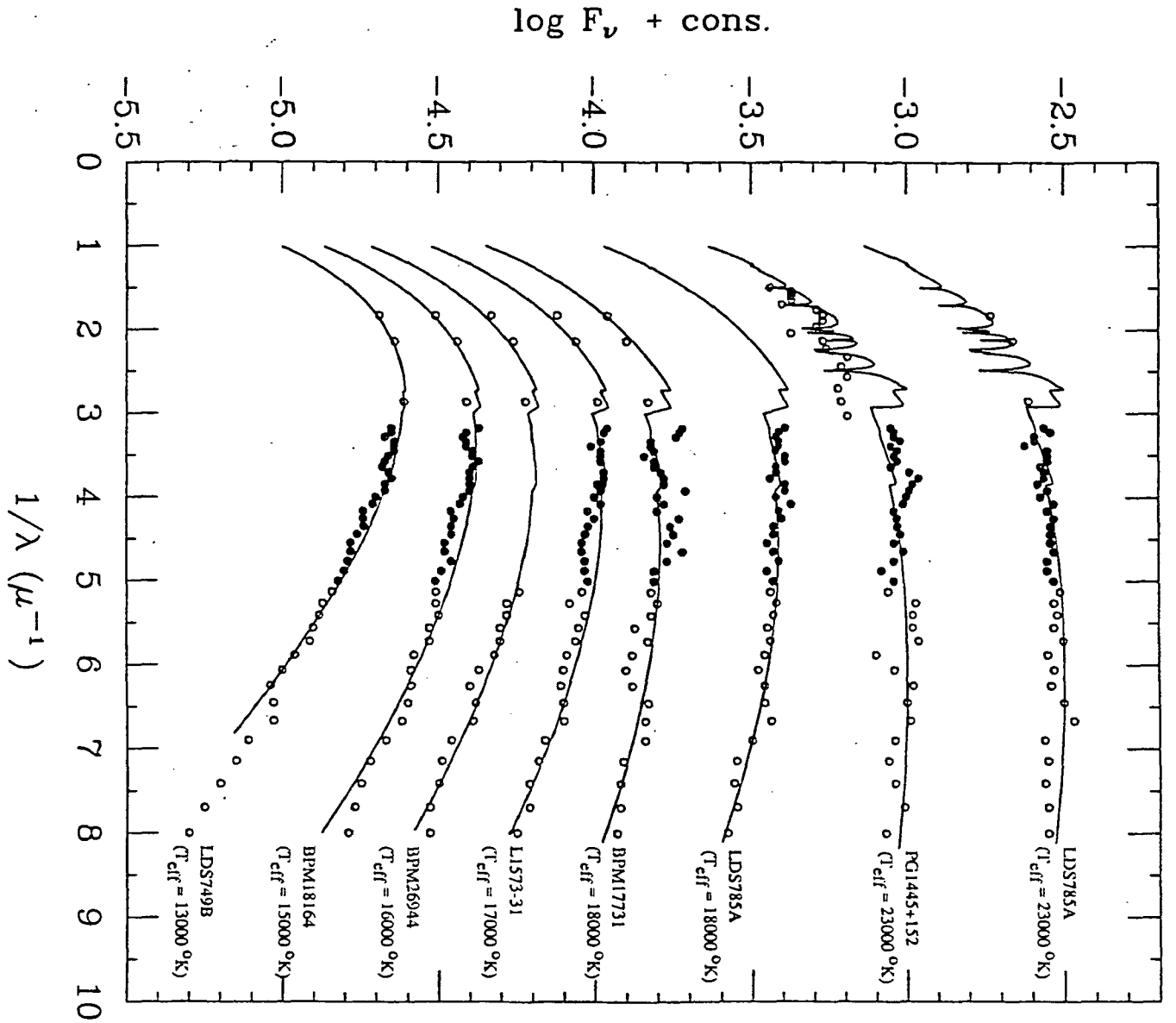


FIG. 5 - The same as Figure 4, except for the stars listed in Table 2. Two comparisons of the continuum of LDS785A with those of models at $T_{\text{eff}} = 23000$ and 18000 K show the sensitivity of these fits. All models shown in Figures 4 and 5 were computed using the He line blanketing, but except for the two models shown here, only continuum points have been plotted.

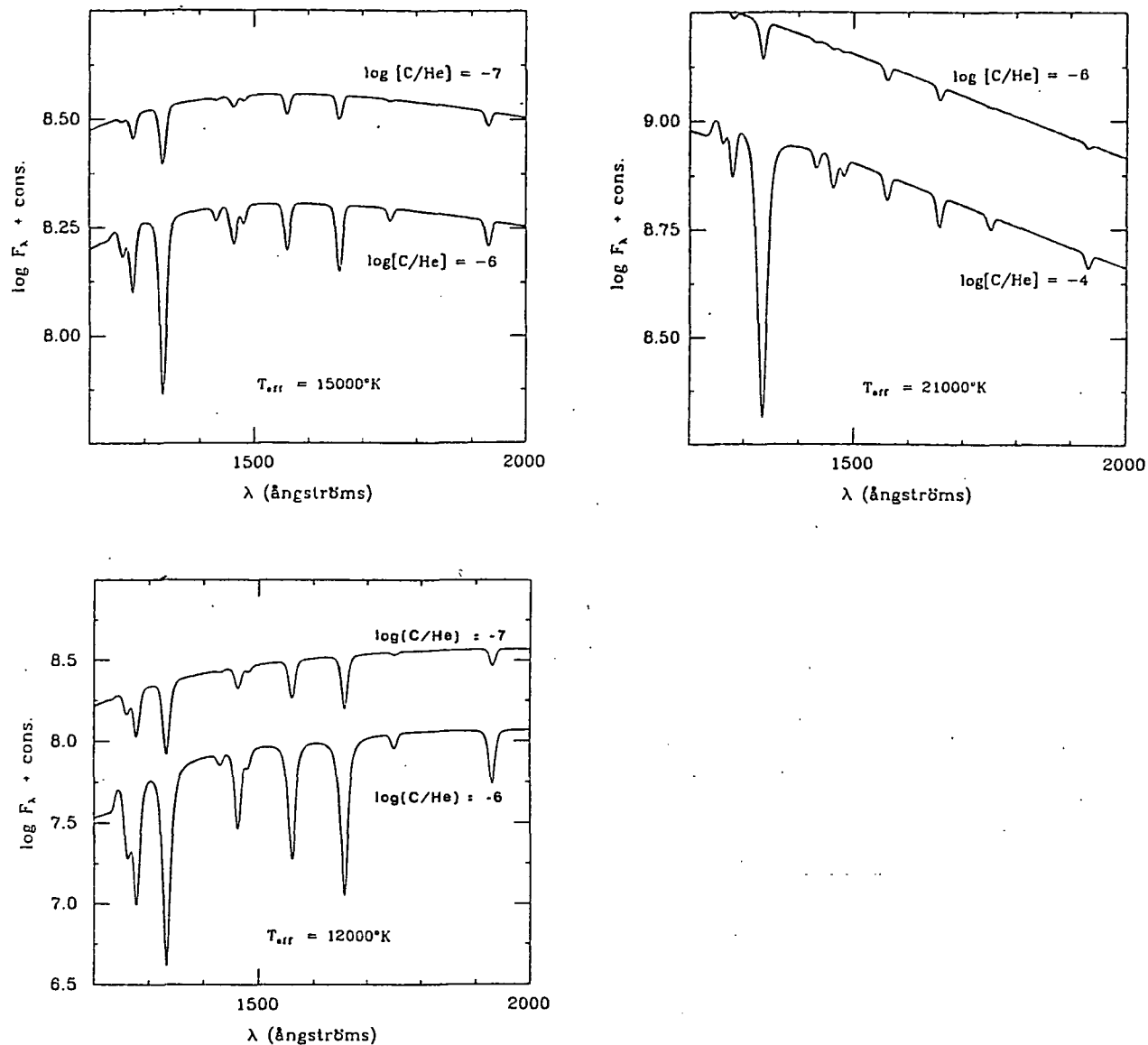


FIG. 6 - Synthetic spectra in the IUE SWP wavelength region for three values of T_{eff} and $\log g = 8$, but with varying carbon abundances.

sources of continuous absorption in the models. Molecules were neglected in the equation of state. The lines of He I have been computed using the broadening theory given in Griem (1974).

The profiles of neutral and ionized carbon lines have been calculated with the $\log gf$ values in Wiese, Smith, and Glennon (1966) and the impact broadening approximation. The van der Waals C_6 factors were computed following Unsöld's (1968) simple expression and Griem's (1974) widths and shifts were used for the Stark effect. In calculating the carbon line profiles, the $T(\tau)$ relations for the pure He models have been used, but the opacity sources for carbon as described by Wegner and Yackovich (1984) for the relevant composition have been added.

b) Comparison between the Models and the Observations

The combined ultraviolet and visual continuum data for stars in Table 1 are shown in Figures 4 and 5 and compared with those computed from our model atmospheres. The observed points are 50 Å averages of the *IUE* continuum data combined either with visual spectral scans or photoelectric photometry. Figure 6 illustrates some of the synthetic ultraviolet spectra in the SWP regime of the *IUE* for different carbon number abundances, C:He, and representative effective temperatures. For all models, the line contours have been convolved with a Gaussian profile of 7 Å half width in order to simulate the instrumental profile of the *IUE*.

Table 3
Atmospheric Parameters Derived for the DB
with Ultraviolet Data

Star	T_{eff} (K)	Other T_{eff} (K)	Upper Limit C:He
LTT11	11000	12110 ^a	-6.5
GD408	13000	13310 ^a	-7.0
Ton 10	16000	17310 ^a 21000 ^c	-7.0
GD303	17000	17180 ^a 19000 ^c	-6.5
PG1411+215	14000		-6.5
PG1445+152	23000	18000 ^c	-6.0
G256-18	16000	15030 ^a	-6.7
GD378	16000	15590 ^a	-6.7
BPM17088	23000	26000 ^c	-6.0
BPM17731	18000	18500 ^b 18000 ^c	-5.5
BPM18164	15000		-6.0
GD358			
L1573-31	17000	15820 ^a	-5.0
BPM26944	16000	18000 ^b	-5.5
LDS749B	13000	13150 ^a 13200 ^b	-6.5
LDS785A		18500 ^b 20000 ^c	-5.0

^aOke, Weidemann, and Koester (1984)

^bWickramasinghe (1983)

^cLiebert et al. (1986)

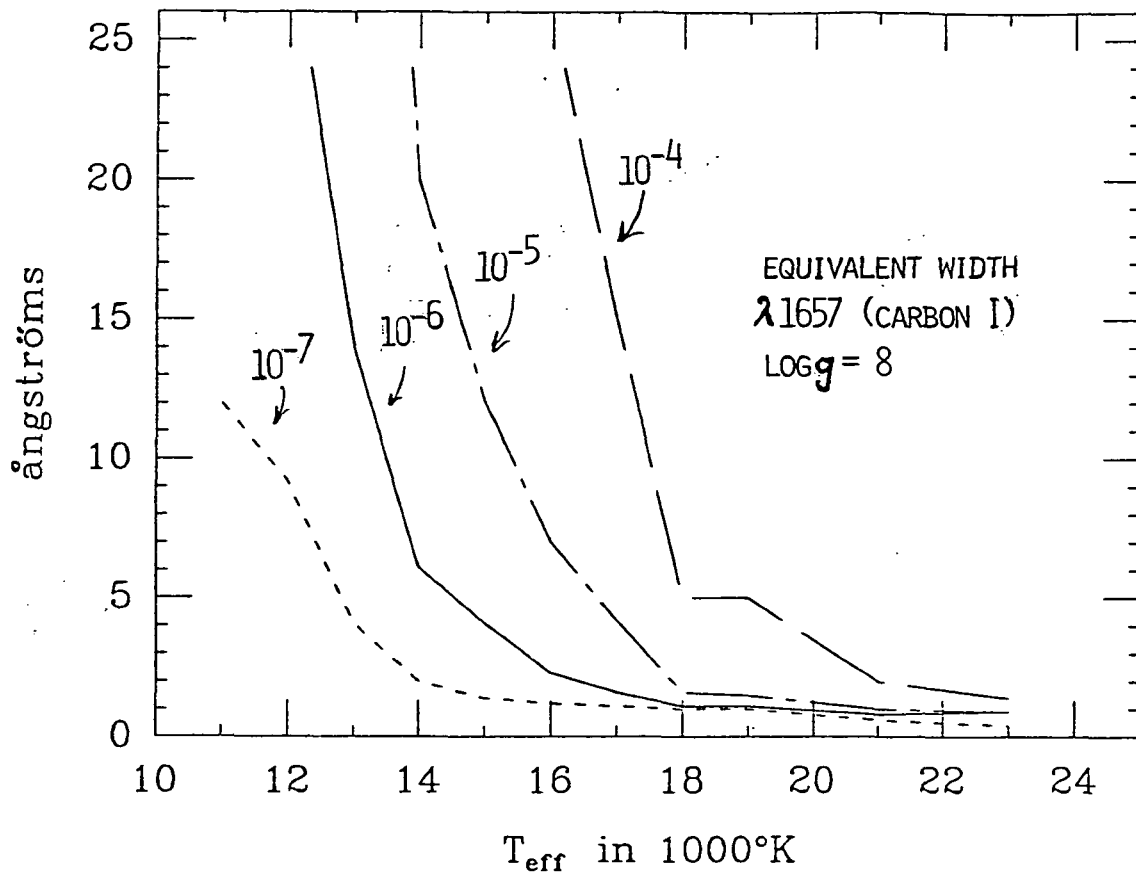


FIG. 7 - Curves of equivalent width for the strong C I resonance line at $\lambda 1657$ for DB stars as a function of T_{eff} for four different constant values of $[\text{C}/\text{He}]$.

From these diagrams, it can be seen that in general, with the currently available ultraviolet spectra, upper limits in the range of $C:He < 10^{-5}$ to 10^{-7} can be established for the DB stars in the range of T_{eff} that has been observed.

Table 3 gives the final estimates of T_{eff} and upper limits for $C:He$ for the DB in Tables 1 and 2. The reason for approximate constancy in these upper limits is basically due to the signal to noise of the observations and the fact that lines of both the C I and C II lines lie in the observed wavelength interval. For T_{eff} below about 18000 K, the C I lines dominate, while for higher effective temperatures, the C II resonance line near $\lambda 1335$ becomes more prominent as the ionization increases and neutral carbon features begin to fade. The behavior of the equivalent width of the strong $\lambda 1657$ line of C I, which was found to be most useful for deriving the upper limits to the atmospheric carbon abundances is shown in Figure 7.

IV. CONCLUSIONS

The lines of the element carbon have been sought in the spectra of the DB white dwarfs. This search, utilizing ultraviolet data from the *IUE*, yielded no convincing evidence for new lines of carbon or any other element besides hydrogen or helium in the spectra of the DB studied. Consequently only upper limits for

carbon have been derived and were found to be in the range of $C:He < 10^{-5} - 10^{-7}$. The actual value for each object, depends mainly on the noise level of the observations, but also somewhat on the adopted hydrogen abundance.

The case of carbon is of particular interest with regard to the relationship between the DB stars that show no evidence for this element and the cooler DQ stars. These latter objects are also considered to be members of the helium-rich white dwarf sequence and show spectroscopic signs of carbon (Cf. Wegner and Yackovich 1984). The DQ show evidence for the hypothesis of a convective dredging origin of the carbon in the proper range of T_{eff} where convection reaches maximum depth (Wegner and Yackovich 1983; Fontaine et al 1984; Pelletier et al. 1985). Consequently, this theory predicts that a maximum carbon abundance occurs near $T_{eff} = 12000$ K and that low carbon abundances occur for $T_{eff} > 14000$ K in the realm of the DB and at low $T_{eff} < 6000$ K.

On the whole, the DB white dwarfs fit in well with these ideas. Pelletier et al. (1985) have determined the observable carbon abundance as a function of T_{eff} and the mass of the helium envelope.

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